The Role of Pragmatic Information in Quantum Mechanics and the Quantum-Classical Transition

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Abstract

I will show how an objective definition of the concept of information and the consideration of recent results about information-processing in the human brain help clarify some fundamental and often counter-intuitive aspects of quantum mechanics. In particular, I will discuss entanglement, teleportation, non-interaction measurements and decoherence in the light of the fact that pragmatic information, the one our brain handles, can only be defined in the classical macroscopic domain; it does not operate in the quantum domain. This justifies viewing quantum mechanics as a discipline dealing with mathematical models and procedures aimed exclusively at predicting the possible macroscopic changes and their likelihood that a given quantum system may cause when it interacts with its environment, including man-made devices such as measurement instruments. I will discuss the informational and neurobiological reasons of why counter-intuitive aspects arise whenever we attempt to construct mental images of the "inner workings" of a quantum system by forcing the concepts of classical information and time into the quantum domain; in this context I will examine the role of pragmatic information as a discriminator in the quantum-to-classical transition.

1 Introduction: the meaning of information and knowledge in physics

Since its birth, a variety of views and interpretations of quantum mechanics were proposed ("Standard", "Copenhagen", "Path-integral", "Hidden Variables", "Many-Worlds", "Transactional", "Consistent Histories", "Informational", etc.). They all invoke the concept of information, yet seldom is it made clear which of the various types, Shannon, algorithmic or pragmatic are meant. And from the beginning, physicists have been arguing about whether the observer and his/her state of knowledge do play an active role in the quantum measurement process, without, however, having the benefit of knowing what is known today about the biophysical mechanisms that control human brain function.

It is quite understandable that terms of such every-day usage as “information” and “knowledge” remained undefined in the physics literature. Yet given some new ideas and experimental results about these two concepts, respectively, it is time to revisit some fundamental discussions of the foundations of quantum mechanics, especially their role in quantum measurements, Gedanken-experiments and the process of preparation of a quantum system (Roederer 2010).

Physicists are accustomed to working with Shannon and algorithmic information. Traditional information theory, however, does not give a universal and objective definition of the concept of information *per se* applicable to all sciences—it is mainly concerned with the mathematical treatment of the *quantity* (and quality) of information, its transmission and its storage. In many situations, however, especially in genetics and brain science, the notion of quantity of information is of little importance: what counts is what information ultimately *does*, not how much it is, in what form it is expressed and how it subjectively appears to our senses or mental images[1].

Rather than attempting to define information *ab initio*, it is more appropriate to start with the concept of *interaction* between complex objects as the “epistemological primitive”, i.e., the primary concept (Roederer 1978, 2005). We can identify two distinct broad categories: 1) Interactions which can always be reduced to a *superposition* of physical interactions (i.e., forces) between the systems’ elementary constituents; 2) Interactions which cannot be expressed quantitatively as a superposition of elementary interactions, but in which *patterns and forms* (in space and/or time) play the determining role on whether or not an interaction is to take place.

Examples of the “force-driven” interactions of the first category are all the purely physical interactions between elementary particles, nuclei, atoms, molecules, parcels of fluid, chunks of solid bodies, planets and stars. The simplest case of an interaction of the second category is an arrangement in which the presence of a specific *pattern* in a complex system leads to a causal, macroscopic and *univocal* change in another complex system, a change that would not happen (or just occur by chance) in the absence of the pattern at the source. Typical examples range from effects on their respective chemical environments of the one-dimensional pattern of bases in the DNA or RNA molecule or the three-dimensional shape of a folded protein, to insects in “orbit” around a light source, to print patterns changing the neural activity and long-term synaptic interconnections in a reader’s brain. Information is then defined as *that which represents the univocal correspondence pattern $\rightarrow$ change*. This is called *pragmatic information* (Küppers 1990) and is the reason why we call this second category “information-driven interactions”. By “univocal” we mean that the interaction process is deterministic and must yield identical results when repeated under similar conditions of preparation (which in turn requires that the results must be intercomparable.) They all require a complex *interaction mechanism* with a reset function (often considered part of one of the interacting bodies) that ultimately provides the energy required to effect the specific change.

There are only three fundamental processes through which the mechanisms of information-driven interactions can emerge (Roederer 2005): 1) Darwinian evolution;

[1] For instance, the genome of the plant *Paris japonica* is 50 times the size (number of base pairs) of the human genome; on the other hand, President Truman’s decision to drop the atomic bomb on Hiroshima was ultimately just a one-bit “yes/no” decision—with enormous consequences.

2) adaptation or neural learning; 3) as the result of human reasoning and long-term planning. In other words, they all involve *living matter*—indeed, information-driven interactions represent the *defining property of life*. The first mechanism is ultimately responsible for the emergence of membranes that allow the encapsulated organic material to maintain a low-entropy state of quasi-equilibrium with the environment; the second mechanism endows organisms with the capability of a probabilistically "most favorable" response to external change. The third mechanism is uniquely human and represents the ultimate source of all artifacts. In summary, any information-driven interaction between *inanimate* complex systems must ultimately be life-generated or -designed, involving at one stage or another purposeful, goal-directed actions by a living system. For instance, an electromagnetic or sound wave emitted by a meteorological lightening discharge does not represent any information-driven interaction; on the other hand, waves emitted by an electric discharge in the laboratory may be part of an overall artificial information-driven interaction mechanism if they are the result of an action with the purpose of causing a desired change somewhere else. Note that information-driven interactions, whether purely biological or in a human-controlled experiment, affect the "normal" physical (non-biological) course of natural events. They all involve processes in complex bodies of the classical macroscopic domain, with time-sequences which strictly obey the dictates of causality, locality, thermodynamics and special relativity.

The concept of "information" does not appear as an active, controlling agent in purely physical interaction processes of category 1 above; it only appears there when an *observer* intervenes (see Roederer 2005, Chapter 5). For instance, in thermodynamics the association between entropy and information arises not from nature per se, but from the way *we* the observers describe or manipulate nature (counting molecules in a pre-parceled phase space; mentally tagging molecules according to their initial states; coarse-graining; looking for regularities vs. disorder; predicting fluctuations; extracting mechanical work based on observed patterns in the system; etc). Similar arguments can be made when we describe black holes as "swallowing information", or decoherence as "carrying away information on a quantum system" (see further below). In these examples, all physical interactions involved are force-driven; whenever we use the term information in their description we really mean "information *for us*, the observers". And when *it is us* who deliberately set the initial conditions of a classical mechanical system or prepare a quantum system, we are converting it into an information-driven system with a given purpose (to achieve a change that would not happen naturally without our intervention). All laboratory experiments, whether a simple classroom physics demonstration or a sophisticated table-top quantum experiment, fall into this category.

There is no such thing as a numerical *measure* of pragmatic information. Pragmatic information cannot be quantified—it represents a correspondence which either exists or not, or works as intended or not, but it cannot be assigned a magnitude. Shannon information, algorithmic information, Fisher information and others are all quantitative measures of novelty, uncertainty, disorder, expectancy, entropy, quality of information, number of binary steps to identify or describe something, error distributions, noise, etc. And here it is where we should turn to the other biological link mentioned at the beginning, namely human brain function, by pointing out that all these purely mathematical

quantities are coupled to highly subjective concepts ultimately related to how the human brain reacts to certain sensory input. In most cases they relate to how the neural cognitive state changes from "not-knowing to knowing", a transition which I like to describe as the reduction of an initial brain state to one of possible "basis states", where each basis state represents the mental image of one possible outcome of expected alternatives (we even might call them "preferred mental states").

Recent studies with functional magnetic resonance imaging, positron emission tomography, diffusion tensor imaging and, at the neural network level, multi-microelectrode recording, are confirming a hypothesis long in use by neurophysicists and computer scientists, namely that the pragmatic information processed by the brain in real-time cognitive tasks is encoded in the brain as a task-specific *spatio-temporal distribution of neural activity* in certain regions of the cerebral cortex (e.g., Tononi and Koch 2008). For instance, given a "shiny red apple", specific neural electrical impulse distributions arise in parts of the prefrontal lobes and in certain regions of the temporal, parietal and occipital lobes, that are nearly the same whether we actually see, hear about, think of, or just dream of that red apple—only the order in which they appear will depend on whether we perceive, imagine or remember. When we study a physical system, the pragmatic information involved represents the correlation between an external pattern (e.g., the positions of a system of mass points, the position of a dial in an instrument, the dots on cast dice) with a specific spatio-temporal neural activity pattern in the prefrontal lobes, corresponding to the knowledge "it's *this* particular state and not any other possible one". The actual information-processing mechanisms in the brain linking one neural distribution with another are controlled by the actual synaptic wiring of the neural networks, which in certain regions, especially the hippocampus and the cerebral cortex, has the ability of undergoing specific changes as a function of use ("plasticity")—the physiological expression of long-term memory.

Modern neurobiology has an answer to the common question: When does a specific distribution of neural firings actually become a mental image? This neural activity distribution does not *become* anything—it *is* the image! In summary, the dynamic spatio-temporal distribution of neural impulses and the quasi-static spatial distribution of synapses and their efficiencies together are the physical realization of the global state of the functioning brain at any instant of time[2].

Quite generally, animal brains handle pragmatic information in sequences of information driven interactions in which one specific spatio-temporal pattern of neural activity is mapped or transformed into another neural pattern—in its most fundamental form, from a physically triggered sensory or interoceptive stimulation pattern to a neural output pattern (stimulating muscle and gland fibers, governing the animal's integral behavior). These processes, as mentioned above, may change the interconnectivity (synaptic architecture) of participating neural networks, leading to long-term

[2]In a gas there are unimaginable many possible dynamic configurations of molecules representing one and the same macroscopic thermodynamic state; in the brain, too, there are unimaginable many possible spatio-temporal distributions of neural activity−however, within certain limitations each one represents a different, *unique* cognitive state. Unfortunately, at the present time, given the number of interacting elements ($\sim 10^{12}$ neurons and $\sim 10^{14}$ synapses) and the discontinuous nature of activity distribution, there is little hope that a quantitative mathematical theory of integral brain function could be developed in the foreseeable future.

storage of information. A memory recall consists of the replay of the original neural activity distribution that had led to the synaptic changes during memory storage; the most important type is the *associative recall*, in which the replay is triggered by a cue embedded in the ongoing neural activity distribution.

The human brain can recall stored information *at will* as images or representations, manipulate them, discover overlooked correlations[3], and re-store modified or amended versions thereof, *without* any concurrent external or somatic input—it can go "off line" (Bickerton 1995). This is information generation par excellence and represents the *human thinking process* (e.g., Roederer 1978). Internally triggered human brain images, however abstract, are snippets (expressed as many different but distinct patterns of neural activity in specific regions of the cortex) derived from stored information acquired in earlier sensory or mental events, and pieced together under some central control (the "main program") linked to human self-consciousness.

The reader may wonder what these purely biological facts have to do with the interpretation of quantum mechanics. Physics is created by human brains, and whenever a physicist conceives or thinks about the model of a physical system or physical process, whether classical, relativistic or quantum, whether one-dimensional or multi-dimensional, his/her brain triggers, transforms and mutually correlates very specific and unique distributions of neural impulses in 3-D space and time. And as I shall discuss below, the fact that the brain is an eminently classical information-processing device[4] that evolved, and is continuously being trained, through informational interactions with the classical macroscopic world, is very germane to how we can imagine, describe and understand the behavior of quantum systems. As a matter of fact, this also applies to classical physics, most notably statistical mechanics and thermodynamics and related paradoxes (Roederer, 2005).

In what follows we shall re-examine some common "classroom examples" of elementary quantum behavior taking into account the preceding discussion of the concept of information.

2 Single qubits

First we examine the *measurement process* as a deliberate "top-down" human intervention in a quantum system. Another such intervention is the process of *preparation* of a quantum system in a given state, which also involves a measurement process at some stage. The equivalent actions in the classical domain are measurement (ideally, without in any way perturbing the system) and setting initial conditions.

Consider the measurement of a qubit; any measurement apparatus has a "quantum end", with which the qubit interacts (e.g., the atoms to be ionized in a particle detector), and a "classical end" that after the measurement exhibits a macroscopic change (e.g.,

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[3] In animals, the time interval within which causal correlations can be established (trace conditioning) is of the order of tens of seconds and decreases rapidly if other stimuli are present (e.g., Han et al. 2003); in humans it extends over the long-term past and the long-term future (for a brief review of human vs. subhuman intelligence, see for instance Balter 2010). Most importantly for our discussion, this leads to the conscious awareness of the past, present and future, and the quantitative conception of time.

[4] Quantum decoherence times in the brain cells would be ten or more orders of magnitude shorter than the minimum time required for any cognitive operation (e.g., Schlosshauer 2007).

voltage pulses, a luminescent screen, position of a pointer, a living or dead cat). It is the physical structure of the device enabling the occurrence of such macroscopic change that *defines* the observable in question. The observer per se is irrelevant during the measurement itself, except that we must not forget that it was a human being who designed the instrument (hence decided what observable to measure), who selected and prepared the system to be measured, and whose brain ultimately expects to receive an image, *the neural correlate* of the change in the macroscopic state of the apparatus as a result of the measurement (knowledge of the value of the observable).

Following the usual von Neuman protocol, let us call $|M\rangle$ the initial state of the apparatus and $|M_0\rangle$,$|M_1\rangle$ the two possible alternative states of the apparatus *after* the measurement. The instrument is *deliberately* built in such a way that when the qubit to be measured is in a basis state $|0\rangle$ before its interaction with the apparatus, the final independent state of the instrument after the measurement will be $|M_0\rangle$, and if the state of the qubit is $|1\rangle$ the instrument will end up in state $|M_1\rangle$. In either case, the state of the qubit remains unchanged (we are assuming this to be a non-destructive measurement). Therefore, for the *composite* state qubit–apparatus we will have the following evolution in time, as determined by the Schrödinger equation: $|0\rangle\,|M\rangle \rightarrow |0\rangle\,|M_0\rangle$ *or* $|1\rangle\,|M\rangle \rightarrow |1\rangle\,|M_1\rangle$.

If the qubit is now in a *superposed state* $\alpha|0\rangle + \beta|1\rangle$ (with $|\alpha|^2$+$|\beta|^2$=1), since the Schrödinger equation is linear in time we will obtain an *entangled* state and the state of the composite system qubit–apparatus will, as long as it is kept isolated from all other interactions, remain a linear superposition: $(\alpha|0\rangle + \beta|1\rangle)|M\rangle \rightarrow \alpha|0\rangle|M_0\rangle + \beta|1\rangle|M_1\rangle$. However, it is an experimental fact that one has never observed a macroscopic system with such peculiar properties as superposition and entanglement (the essence of the Schrödinger cat paradox): the end state of the composite system will always be either $|0\rangle M_0\rangle$ or $|1\rangle|M_1\rangle$ with $|\alpha|^2$ and $|\beta|^2$ the probabilities to obtain either result, respectively (Born rule). The original qubit emerges from the measurement process in the corresponding eigenstate; this transition is called *state reduction*. The process that prevents any possible one-to-one correspondence between the coefficients α, β and the features of a macroscopic change in the apparatus is called *decoherence*. According to our definition of pragmatic information, decoherence and state reduction thus express the fundamental fact that *no information can be extracted experimentally on the superposed state of a single qubit* (note that together with the Born rule, this fact indirectly confers physical legitimacy to the representation of quantum states and observables by Hilbert space vectors and Hermitian operators, respectively, and the use of linear algebra to describe their interactions and transformations).

All the preceding is related to the "no cloning" theorem (Wooters and Zurek 1982). From the informational point of view, if we *could* make N ($\rightarrow \infty$) copies of a single qubit in a superposed state, a correspondence could indeed be established between the original pair α, β and some macroscopic feature linked to the statistical outcome of measurements on the N copies (in the case of a qubit, for instance the average values of some appropriate observables). This would be tantamount to extracting pragmatic information from the original single qubit. What is possible, though, is to repeat exactly N times the *preparation process* to obtain N separate qubits in the same superposed state (like retyping a text on blank sheets repeatedly, instead of Xeroxing the original

N times). Each qubit of this set can then be subjected to a measurement, and the parameters α, β extracted from the collection of results (this is, precisely, how the probabilities $|\alpha|^2$ and $|\beta|^2$ are obtained experimentally[5]).

Note that the preparation of a qubit in a given superposed state requires the intervention of complex macroscopic devices and three steps of action on a *set* of qubits: 1) measurement of an appropriate observable (which leaves each qubit in an eigenstate of that observable); 2) selection (filtering) of the qubits that are in the desired eigenstate; 3) unitary transformation (a rotation in Hilbert space) to place the selected qubit in the desired superposed state. In this procedure a preparer has converted a certain *macroscopic* pattern (embedded in the physical configurations of the preparation process) into two complex parameters of a quantum system (e.g., the wanted α and β coefficients of the qubit). According to our definition, doesn't such correspondence represent genuine pragmatic information? No, because it would not be univocal: given a *single* qubit in an unknown state, an observer could never reconstruct through measurement the original macroscopic configuration used, or steps taken, in the preparation process. The only way to do so, is to remain in the macroscopic domain and *ask* the preparer (classical information from brain to brain!). Once known via such a macroscopic route, it will in principle be possible to *verify* (but not to determine from scratch) the information about α and β.

3 Entangled qubits

Take two qubits *A* and *B* that are maximally entangled in the antisymmetric Bell state $\Psi^- = 1/\sqrt{2}(|0\rangle_A|1\rangle_B - |1\rangle_A|0\rangle_B)$ at time t_0. We may imagine qubit *B* now being taken far away. If nothing else is done to either, we can bring *B* back, and with some suitable experiment (e.g., interference) demonstrate that the total state of the system had remained entangled all the time. If, instead, at time $t_A > t_0$ a measurement is made on qubit *A* leaving the composite system reduced to either state $|0\rangle_A|1\rangle_B$ *or* $|1\rangle_A|0\rangle_B$, qubit *B* will appear in either basis state $|1\rangle_B$ *or* $|0\rangle_B$, respectively, if measured. The puzzling thing is that it does not matter *when* that measurement on *B* is made—even if made *before* t_A. Of course, we cannot predict which of the two alternatives will result; all we can affirm is that the measurement results on each qubit will appear *to be correlated*, no matter the mutual spatial distance and the temporal order in which they were made[6]

The result of all this is that it appears as if the reduction of the quantum state of an entangled system triggered by the measurement of one of its components is "non-local in space and time". Yet correlation does not mean causation in the quantum domain: nothing strange happens at the macroscopic level: the state reduction cannot be used to transmit any real information from *A* to *B*. In terms of our definition of pragmatic

[5]Since α and β are two normalized *complex* numbers, in order to determine, say, their relative amplitudes and phase statistically, it is necessary to obtain *two* sets of measurement data, corresponding respectively to two non-commuting observables (*N*/2 measurements in each set).

[6]One could argue that in the case of a measurement on *B* at an earlier time $t_B < t_A$, it was *this* measurement that "caused" the reduction of the qubits' composite state, but the concepts of "earlier" and "later" between distant events are not relativistically invariant properties.

information, there is no "spooky" action-at-a-distance: an experimenter manipulating *A* has no control whatsoever over *which macroscopic change* shall occur in the apparatus at *B*, and vice versa. The spookiness only appears when, in the *mental* image of a pair of spatially separated entangled qubits, we force our (macroscopic) concept of information into the quantum domain of the composite system and think of the act of measurement of one of the qubits as *causing* the particular outcome of the measurement on the other.

The previous discussion also says something about how we tend to think intuitively of time at the quantum level. Like information, *time is a macroscopic concept*, to be measured on the basis of macroscopic changes in a clock (or in the position of a star), occurring between coincidences with some specific macroscopic events (even an atomic clock must have classical components to serve as a timepiece). We can assign time marks to a quantum system only when it interacts *locally* with (or is prepared by) a macroscopic system. In the case of a wave function $\Psi(\mathbf{x}, t)$, the time variable refers to the time, measured by a macroscopic clock *external* to the quantum system, at which $|\Psi|^2$ is the probability density of actually observing the quantum system at the position $\mathbf{x}$ in configuration space, which is also based on measurements with macroscopic instruments. Non-locality in space and time really means that for a composite quantum system, the concepts of distance and time interval between different superposed or entangled components *are undefined* as long as they remain unobserved, i.e., free of interactions with macroscopic systems (for a postulate on atemporal evolution, see Steane, 2007). Because of this, it may be unproductive trying to find a modified form of the Schrödinger equation, or any other formalism, to describe quantitatively what happens "inside" a quantum system during the process of state reduction.[7]

Yet another insight into these questions can be gleaned from the re-examination of the so-called *quantum teleportation* of a qubit (e.g., Bouwmeester et al., 1997). An entangled pair of qubits in the antisymmetric Bell state $\Psi^- = 1/\sqrt{2}(|0\rangle_A|1\rangle_B - |1\rangle_A|0\rangle_B)$ is produced at time t_0 and its components are taken far away from each other. At time $t_A > t_0$ an unknown qubit in superposed state $\alpha|0\rangle_C + \beta|1\rangle_C$ is brought in and put in interaction with qubit *A*. The total, composite, state of the three-qubit system is now $1/\sqrt{2}(\alpha|0\rangle_C + \beta|1\rangle_C)(|0\rangle_A|1\rangle_B - |1\rangle_A|0\rangle_B)$, which can be shown algebraically to be equal to a linear superposition of four Bell states in the *A*-*C* subspace, with coefficients that are specific unitary transforms of the type $(-\alpha|0\rangle_B - \beta|1\rangle_B)$, $(+\alpha|1\rangle_B - \beta|0\rangle_B)$, and so on. Therefore, if a measurement is made on the pair *A*-*C* of any observable whose eigenstates are the four Bell states, the state of the entire system will collapse into just one of the four terms, with the qubit at *B* left in a superposed state with coefficients given by the parameters α, β of the now vanished unknown qubit *C*. If the observer at point *A* informs *B* (through classical, macroscopic means) which basis Bell state has resulted in the measurement—only two bits are needed to label each possible basis state—observer *B* can apply the appropriate inverse unitary transformation to his qubit, and thus be in possession of the teleported qubit *C* (defined by the unknown coefficients α and β).

The puzzling aspect of this procedure is that it looks as if the infinite amount of

[7] For instance, a theoretical or experimental derivation of "average trajectories" in a double-slit experiment (e.g., Kocsis et al. 2011) provides the geometric visualization of something on which, for an individual particle, pragmatic information could never be obtained!

information on two real numbers (those defining the normalized pair of complex numbers α and β) was transported from *A* to *B* by means of only two classical bits. Even worse: there is even a 25 percent chance that the observer at *B* was in possession of the unknown qubit already *before* receiving those two key bits!

The answer is that, again, according to our definition, the parameters α, β *do not represent pragmatic information*. There is no way to verify the teleportation of a *single* qubit; the only way verification could be accomplished is through a *statistical* process, repeating the whole procedure *N* times, from the identical preparation of each one of the three qubits *A*, *B*, *C* to the actual measurement of the teleported qubit (however, see footnote[5]!). If we determine the frequencies of occurrence N_0 and $N_1 (= N - N_0)$ of the $|0\rangle_B$ and $|1\rangle_B$ states, and express the teleported qubit state in its polar (Bloch sphere) form $|\Psi\rangle = \cos(\theta/2)|0\rangle + \exp(i\phi)\sin(\theta/2)|1\rangle$, it can be shown that the number of *statistically significant* figures (in base 2) of θ and ϕ to be obtained is equal to the *total number 2N* of bits transmitted classically (i.e., macroscopically) from *A* to *B*, so that from the statistical point of view, there is no puzzle! This shows that there is *no way* of teleporting pragmatic information and, as a consequence, macroscopic objects!

4 The process of decoherence

Let me address now the still contentious question of what, if any, *physical* processes are responsible for decoherence in the transition from the quantum domain to the macroscopic, classical, part of a measurement apparatus (for details, see, e.g., Schlosshauer 2008). For this purpose, we consider a model of the measuring apparatus that consists entirely of mutually interacting qubits—lots of them, perhaps 10^{22} or 10^{23}—with one of which the external qubit to be measured enters into unitary (non-destructive) interaction at time t_0. In our model, the apparatus qubits represent a complex web in some initial or "ready" state, designed in such a way that, as the local unitary interaction processes multiply and propagate, only two distinguishable macroscopic end states M_0 and M_1 can be attained, realized as two macroscopic spatially or temporally different forms or patterns (the so called pointer states, represented in mutually orthogonal Hilbert subspaces of enormous dimensions). The key physical property of this construction is that final macroscopic state actually achieved will depend on the *actual* basis state of the measured qubit (see discussion in section 2).

If the qubit to be measured is now in a superposed state, the first physical interaction at time t_0 would create an entangled state of the system "qubit–first apparatus particle" which through further unitary inter-component interactions would then expand to the entire composite system "qubit–apparatus" in a cascade of interactions and further entanglements throughout the apparatus. Accordingly, the classical end of the apparatus also should end up in a superposed state (the Schrödinger cat!) and since in principle the interactions are unitary, the whole process would be reversible. Obviously, somewhere in the cascade of interactions there must be an irreversible breakdown of the entanglement between the original qubit and the instrument, both of which will emerge from the process in separate but correlated states, either $|0\rangle$ and M_0, or $|1\rangle$ and M_1, respectively.

Extractable pragmatic information appears only in the classical end of this cascade.

It would not be legitimate to trace the whole process backwards into the quantum end and conclude that there is an apparent "back-propagation of causation" in this picture, in which something that happens physically and locally inside the apparatus (and in the environment—see below) has a retro-effect on the original qubit. As mentioned above: correlation does not necessarily mean causation! Referring to what we said in the preceding section about the atemporal character of a quantum system, as long as the cascade is operating in the quantum domain unitarily and reversibly, "time does not flow"; there is no past, present and future in the classical sense. As to the probabilistic nature of the results in case of repeated measurements (the Born rule), the breakdown of coherence, regardless of its physical nature, will dictates the correspondence between the instrument's state achieved and the basis end state of the measured qubit. This correspondence does represent macroscopic pragmatic information, but of course it is statistic in nature. The whole framework of *quantum information* theory and technology is based on the consistency of this kind of *classical* correspondence: the relation of a given set of qubits in prepared eigenstates (a classical input pattern) correlated through intermediate unitary quantum interactions in a quantum computing device to another set of qubits in basis states (a classical output pattern).

A striking example of decoherence is that of a *"non-interaction"* measurement (Elitzur and Vaidman, 1993). Thus far we have implicitly considered only intrinsic binary variables of the qubit/particle, like spin, polarization, energy levels, etc. Let us turn now to an external variable like the two possible paths of a photon in a Mach-Zehnder interferometer or double-slit experiment, or an electron in a Stern-Gerlach experiment. In either case we have two possible basis states, say the trajectories $|left\rangle$ and $|right\rangle$ (in the Schrödinger picture, a wave function represented by two separate wave packets). A superposed "which-path" state of the particle will be $\alpha|left\rangle + \beta|right\rangle$.

We now interpose a non-destructive measurement device in the left path that can be turned on during a very brief interval of time after the superposed state was created. The device has the property that (i) when the particle is in the eigenstate $|right\rangle$ and the counter was turned on during the time when the particle wave packet is supposed to pass were it to travel on the left path, it will show the state M_0 (no count); and (ii) when the particle is in the eigenstate $|left\rangle$, the instrument will exhibit a macroscopic change into state M_1 (e.g., emit a blip or click).

If the particle is in a maximally superposed which-path state such as $1/\sqrt{2}(|left\rangle + |right\rangle)$, it will get entangled with the quantum end of the apparatus, in principle leading to the composite state $1/\sqrt{2}(|left\rangle M_1 + |right\rangle M_0)$ of the particle–apparatus system. However, decoherence will occur, and, with 50/50 probability the state of the composite system will end up reduced to either of the independent states "left-path and count" or "right-path and no-count".

We are tempted to ask: What actually has caused the collapse when the final state $|right\rangle M_0$ arises, which our classical mind wants to interpret as a particle "sailing through unscathed" along the right path without, apparently, ever having been able to affect the measurement apparatus in the left branch? Since in this non-interaction measurement a state reduction obviously *did* take place, a decoherence process must have occurred in the "untouched" but turned-on detector—unfortunately we will never be able to find out, i.e., be able to extract pragmatic information about this by "looking into the innards" of the apparatus while decoherence is occurring (if we do, we would

be interfering with yet another apparatus with which the participating elements will get entangled and then decohere). Also, as we shall mention below, in a non-demolition interaction, decoherence does not involve any energy transfer from qubit to apparatus, whether it leads to a macroscopic change or not in the latter (the free energy required for any such change is always provided by a local reservoir in the instrument). If the detector was not turned on *exactly* during the time interval in which the corresponding partial particle wave packet would be going through the interaction point (note that this time is dictated at the macroscopic level!), no reduction would take place, and the particle would remain in a superposed which-path state.

There has been considerable discussion during the last decades about the possible physical causes of decoherence. Opinions seem to converge to "it's the environment" (e.g., Zurek 2007). It is physically impossible to shield the composite system qubit–apparatus completely from outside influences (gravity, long-wave electromagnetic radiation, thermal and vacuum fluctuations, etc.). Since by definition a measurement apparatus must be able to respond macroscopically with a change in form or pattern in order to yield extractable pragmatic information (usable by a human observer), at some stage the apparatus will have to be *sufficiently complex*, and so will be the cascade of interactions; thus, the more vulnerable the combined system will be to stochastic perturbations. Times of decoherence have been calculated for highly simplified models, and they usually turn out to be extraordinarily short (order of 10^{-14} s to much less). Schlosshauer (2007) gives examples; he also discusses cases in which there is no exchange of energy with the environment (non-dissipative decoherence). Quite generally, the decoherence mechanism is still a subject of active investigation (see review by Adler, 2007).

Measurement processes and their apparatuses are *artifices*—human planned and designed for a specific purpose. However, note that the preceding discussion on decoherence can be applied to the case in which we replace the artificial measurement apparatus with the *natural environment per se*[8]. Just replace the word "apparatus" with "the environment" with which a given quantum system willy-nilly interacts and gets entangled. As long as this entanglement persists, the given quantum system will have lost its original separate state, and only the *composite* quantum system–environment will have a defined state, however complicated and delocalized. Now, if the interaction with the environment leads to a *macroscopic* change somewhere (potentially verifiable through classical information-extraction by an observer, but independently of whether such verification actually is made), it will mean that decoherence has taken place and that the state vector of the original quantum system will have been reduced to one of its original eigenstates pertinent to the particular interaction process.

This is usually described as "entanglement with the environment carrying away information on a quantum system", or "information about the system's state becoming encoded in the environment". However, I would like to caution about the use of the concept of information in this context, in which no previous design, purpose or goal

[8]Even classical measurement processes require participation of the environment. When you measure the size of an object with a caliper, you can do that in total darkness, because the caliper interacts directly (elastically) with the object, but if you measure it with a ruler, you need to submerge everything in a "bath of photons" whose scattering or reflection is what your optical system uses to extract the wanted information on object–apparatus interaction.

can be identified and through which no specific signal can be sent. There is no loss of pragmatic information in decoherence, because there wasn't any there in the first place. A much less "anthropomorphic" way is to say: "*A quantum system continuously and subtly interacts with its environment and gets entangled with it; if decoherence occurs, a macroscopic change in the state of the environment will appear somewhere (information about which could eventually be extracted by an observer), and the state of the quantum system will appear reduced to some specific basis state in correspondence with the environmental change in question*." Measurement instruments are environmental devices specifically designed to precipitate decoherence and steer it to into certain sets of possible final macroscopic states. The "amazing aspect" of quantum mechanics are not the so-called paradoxes, but *the fact* that statistical probabilities of the outcomes of many repeated measurements can be determined under given conditions of preparation.

An ensemble of identically prepared quantum systems (e.g., a chunk of chemically pure radioactive material) thus turns probabilistic because it is unavoidably "submerged" in a gravitating, fluctuating, thermodynamic macro-world, and will decay into a mixture of quantum entities in eigenstates [9] (e.g., with an α-particle either still inside or already outside a nucleus). On the other hand, the laboratory measurement of a quantum system may be viewed as a case in which the environment was deliberately altered by interposing a human-made apparatus, which then altered in a "not-so-subtle" way the time evolution of the system (we should really say: the time evolution of potential macroscopic effects of the system) by greatly increasing the chance of decoherence. In summary, what we have called the cascade of entanglements in a quantum measurement also involves a stochastic ensemble of outer environmental components with which the instrument's components are in subtle but unavoidable interaction.

A collateral consequence of natural decoherence is that any peculiar quantum property like superposition will have little chance of spreading over a major part of a macroscopic object, which indeed will behave classically whenever observed—there always seems to be a natural limit to the complexity of a quantum system in a pure superposed state beyond which it will decohere. In other words, the classical macroscopic domain, in which life systems operate and information can be defined objectively, consists of objects whose constituents have decohered into eigenstates (mainly, of their Hamiltonians). Quantum behavior of a macroscopic system is *not* forbidden (a Schrödinger cat *could* be in a superposed state of dead and alive at the same time!), but its probability and duration would be ridiculously small.[10] This also explains the fact that many artificial quantum systems are very unstable in a superposed state, and thus very difficult to handle in the laboratory—a fact that represents one of the biggest challenges to

[9] With the decay times depending on the original wave function of the individual nuclei, as well as on subtle but unavoidable interactions of the latter with the environment leading to possible fluctuations in the exponential decay of the ensemble.

[10] Organic macromolecules deserve special consideration, but are outside the scope of this article. They behave classically and are capable of encoding pragmatic information in the form of stable patterns (order of bases in DNA, shape of folded proteins). Decoherence *within* a molecule? Somewhere in this lies hidden the transition from non-life to life (Roederer 2005). On the other hand, experiments in condensed matter physics are underway to artificially extend as much as possible the threshold in some materials beyond which decoherence dominates (e.g., Cho 2010). And some macromolecules like ^{70}C have been shown to exhibit quantum behavior (with ulterior decoherence) in diffraction experiments (Hackermüller et al. 2004)

quantum computing.

5 Concluding remarks

From the previous discussion it is advisable to refrain from using the classical concept of pragmatic information indiscriminately in the quantum domain—even in Gedanken-experiments! Yet quite commonly we do, especially when we teach—but then, as mentioned above, we should not be surprised that by *forcing* the concept of information, and for that matter, the concept of macroscopic time, into the quantum domain, we are triggering mental images of "weird" behavior that is contradictory to our every-day macroscopic experience.

To me, the problem of the interpretation of quantum mechanics is not just of a philosophical nature but an eminently pedagogical one. For instance, how should one answer correctly the often-asked question: Why is it not possible, even in principle, to extract information on the actual state of a *single* qubit? Because *by the definition of information*, to make that possible there would have to exist some physical paradigm by means of which a change is produced somewhere in the *macroscopic* classical domain that is in one-to-one correspondence with the qubit's parameters immediately prior to that process. Only for eigenstates (basis states) can this happen—decoherence prevents the formation of any macroscopic trace of superposed states. In the case of an initially superposed state, the end state of the qubit will always appear correlated with the end state of the macroscopic system, i.e., will emerge reduced to a correlated or preferred basis state. In somewhat trivial summary terms, quantum mechanics can only provide real information on natural or deliberate *macroscopic imprints* left by a given quantum system that has undergone a given preparation, eventually interacts unitarily (reversibly) with other quantum systems forming a composite quantum system, which then interacts irreversibly with the surrounding macroscopic world[11].

So what are the coefficients in a qubit state like $\alpha|0\rangle + \beta|1\rangle$? They are *parameters in a model representation* of the system in 2-D complex Hilbert space, which within an appropriate mathematical framework enables us to make quantitative, albeit only probabilistic, predictions about the system's possible macroscopic imprints on the classical domain. We may call α and β information, and we do, based on the fact that we can prepare a quantum system in a chosen superposed state—the common usage of the terms "quantum bit" and "quantum information" testifies to this. Yet in doing so we are always obliged to point out its "hidden nature", because of the impossibility of retrieving it!

What we normally call *quantum information* is not the type of pragmatic information which our brains are designed to handle in the first place. So where and how does "real information" appear in quantum computing? As discussed before, the preparation of an ensemble of quantum systems with respect to some specific observables (some specific Hilbert sub-space) necessarily will involve, like any measurement, an artificial macroscopic setup that leaves at least some elements of the ensemble in given

[11]This is, in essence, what Heisenberg stated already in 1927: "A particle trajectory is created only by the act of observing it"!

known basis states (of those observables). This set of eigenstates (or the corresponding eigenvalues) can be viewed as an initial classical "pattern" (remember that basis states behave classically in a measurement). The art of quantum computing consists of subjecting this quantum ensemble to appropriate unitary evolution through physical interactions in such a way that a final state can be reached in which at least some of its elements end up in a (usually different) set of *verifiable* basis states. The final set of eigenvalues will then represent a *classical* pattern that will be in univocal correspondence with the *classical* pattern of the initially prepared basis states. This correspondence, by definition, does indeed represent legitimate pragmatic information.

Obviously, during the time interval between the initial and final states, any extraneous non-unitary intervention, whether artificial (a measurement) or natural (decoherence), will destroy the macroscopic input-output correlation. Indeed, in this interim interval, the proverbial mandate of "don't ask, don't tell" applies (Roederer 2005)—not because we don't know *how* to extract relevant information to answer our questions, but because pragmatic *information per se does not operate in the quantum domain.*

6 Summary

The concept of information can only be defined objectively in the macroscopic, classical domain. It represents a physical, causal and univocal correspondence between a pattern and an ensuing specific macroscopic change caused by some complex interaction mechanism which necessarily involves living matter directly (in the present) or indirectly (in the past). In physics it only appears in relation to an "observer", i.e., an experimenter, mental modeler, theoretician, etc., who interacts directly or indirectly, physically or mentally in Gedanken-experiments, with the system chosen. The consequences for quantum mechanics are, in brief:

- A univocal correspondence between the properties (parameters) of a quantum system and some observable macroscopic property is possible only for eigenstates (of the pertinent observable). The properties of a superposed state cannot be mapped onto the macroscopic, classical environment.

- Whenever we model or imagine a quantum system as if it was handling pragmatic information, the appearance of counterintuitive behavior is inevitable because pragmatic information and time do not operate within the quantum domain.

- Nothing that transcends physically from quantum systems and their interactions to the macroscopic domain violates relativity, causality and locality.

- There is a natural limit to the complexity of a quantum system in order to remain stable in a superposed state or a unitary evolution thereof.

- The quantum-to-classical transition is a fuzzy boundary between two domains in one of which, the "outer one", decoherence reigns, the component elements are in stable eigenstates of their Hamiltonians, information and time can be unambiguously

defined, and information–driven interactions can occur (life and human intelligence are possible).

As a consequence of the above, we should view the Schrödinger equation for a single quantum system as encoding the evolution of its potential *macroscopic* effects on the environment (or a measurement apparatus), rather than the time-history of intrinsic properties ascribed to the quantum system *per se*.

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